

Recent Studies of the Cosmic-Ray Latitude Effect at High Altitudes

A. T. BIEHL, R. A. MONTGOMERY, H. V. NEHER, W. H. PICKERING, AND W. C. ROESCH

California Institute of Technology, Pasadena, California

With an improved Geiger counter telescope, having an angular aperture of about $\pm 15^\circ$ from its axis, a series of balloon flights was made in August and September, 1947, at seven stations extending from San Antonio, Texas, to Saskatoon, Canada. The axis of the telescope in all cases was oriented in a vertical direction. All sets of equipment were compared with a standard to reduce all results to a common basis. The standard sets, in turn, were compared with an accurately constructed telescope which had been used to make an absolute determination of cosmic-ray intensity at the vertical in Pasadena.

Two flights were made from each of the seven stations. The agreement between flights made within a few hours of each other at a given station is very good. Results from two flights made at a given station several days apart are not in general as consistent. Likewise, no monotonic increase of the radiation with increase of latitude was observed. Evidence is presented for rather large fluctuations at high altitudes of the lower energy components of cosmic rays. Some of the reasons for these fluctuations are discussed.

I. INTRODUCTION

IN 1939-1940 Millikan, Neher, and Pickering made a series of balloon flights in India using Geiger counters in vertical double coincidence.^{1,2} These flights were made at three different magnetic latitudes 3° , 17° , and 25°N . The significant results were that within the uncertainty of the measurements there was no change in the radiation coming in near the vertical from 3° to 17° while in going to 25°N there was an increase of 21 percent. This was interpreted as meaning that in the primary energy spectrum there were relatively few, if any, particles lying within the energy range from 17 down to 15 Bev. Likewise, the increase in going from 17° to 25° was interpreted as being due to primary charged particles in the energy range 15 down to 12.5 Bev.

To extend these measurements to other latitudes a series of similar observations was made in 1941-42 in Mexico and the United States.³ Those in Mexico were made at Acapulco (Mag. lat. 25.6°N), Valles (Mag. lat. 31°N) and Victoria (Mag. lat. 33°N). It was found at that time that there was little if any increase in going north from 25.6° to 31° . This was again interpreted as due to a deficiency in the primary

radiation in the energy range 10.3 to 8.6 Bev. At Victoria the radiation had definitely increased over its value at Valles, showing that the primary spectrum contained appreciable numbers of particles of energies in the range 8.6 to 7.5 Bev. Several flights at Pasadena showed a pronounced increase over the value obtained at Victoria and this was evidence that the primary spectrum contained particles lying between 7.5 and 5.8 Bev.

In extending the observations farther north, two stations, St. George, Utah, and Pocatello, Idaho, were chosen where one flight at each location was made in March, 1942. The results of these flights showed that within the rather large experimental uncertainties there was a marked increase of about 14 percent at the maximum of the curves in going from Pasadena to St. George, but no increase from St. George to Pocatello. This latter plateau was interpreted as meaning that there were no particles in the energy range from 4.4 to 2.9 Bev.

To check this apparent distribution of particles in the primary energy spectrum and to extend the observations as far north as seemed practical, a new series of flights has been made at seven stations extending from San Antonio, Texas to Saskatoon, Canada. These flights were made with improved equipment of higher resolving power and, in an attempt to minimize secular changes, the whole series was completed

¹ H. V. Neher and W. H. Pickering, *Phys. Rev.* **61**, 407 (1942).

² R. A. Millikan, H. V. Neher, and W. H. Pickering, *Phys. Rev.* **61**, 397 (1942).

³ R. A. Millikan, H. V. Neher, and W. H. Pickering, *Phys. Rev.* **63**, 234 (1943).

in a little under four weeks during August and September, 1947.

II. APPARATUS AND PROCEDURE

A detailed description of the apparatus used appears in the preceding paper of this journal. To summarize, a new type of light-weight, all-metal Geiger counter was used. Eight such counters connected in parallel were made into a tray and three trays were used in each telescope. The separation of the two outer trays was such that the telescope had an aperture of about 15° on all sides of its axis. This is to be compared with the apparatus previously used where the maximum angle from the zenith in one direction was 45° and 25° at right angles to this. The area of the trays of counters was made of such a size that the statistical errors in the counting rates were negligible in determining the maxima of the curves.

The triple coincidences were transmitted by radio to the ground where they were received, scaled down, and recorded on a moving tape. Temperature and pressure data were also transmitted and recorded on the same tape.

In choosing stations from which to send up our balloons we were governed by the availability of helium or hydrogen and by the desire to get a good representation of latitudes. The stations finally selected are given in Table I.

In the period August 27 to September 24, 1947, two successful flights were made at each of these stations except Saskatoon where one good flight was made and only a few good points were obtained around the maximum of the curve for the second flight. The stations were visited in the order given except for St. George. We had intended making flights from Oklahoma City, Oklahoma, but were prevented from doing so by high winds. On the return trip to Pasadena we made two flights from St. George to fill in this gap. The launchings were actually made from sites which were isolated, so that our receiver would not pick up ignition noise from passing cars, and which were located so that the equipment would land in settled territory and have a good chance of being returned to us. Of the 20 instruments sent up 17 have been returned. Of these, two were those released from St. George, Utah, and almost certainly came down in very

rugged country. The average geomagnetic latitude during a flight is quite well represented by that of the stations given above, since the balloons did not drift far from an E-W line.

Before each flight the counter telescope to be flown was placed beside a standard set and the two permitted to count until the ratio between their counting rates had been determined to within 1 percent. After returning to Pasadena the standard set was compared with a carefully constructed telescope having a known geometry which had been used to make an absolute determination of the vertical counting rate out-of-doors in Pasadena. It was then possible to reduce all measurements to an absolute value. The counting rates during the flights were corrected for efficiency and accidentals.

Figure 1 illustrates some of the procedures in inflating the balloons and in launching the instrument. Dr. Millikan was a most valuable member of the expedition and took an active part in much of the preparation.

III. DATA

In Fig. 2 are presented the results of these experiments. The number of counts received per unit solid angle per square centimeter per minute from the vertical direction is plotted against the depth below the top of the atmosphere in meters of water equivalent. The number of counts will differ from the number of ionizing rays because of the effects of showers for which no corrections were made.

Counts were averaged over four minute intervals. For the exponentially changing rates encountered, calling this average the counting rate at the middle of the interval causes an error of a few tenths of a percent at the most. The probable error in the counting rate due to the finite number of counts recorded was about 1.5

TABLE I. Flight stations.

Station	Mag. lat.
San Antonio, Texas	38.5°N
Fort Worth, Texas	41.7
St. George, Utah	44.8
Omaha, Nebraska	51.3
Rapid City, South Dakota	53.3
Bismarck, North Dakota	56.0
Saskatoon, Canada	60.0

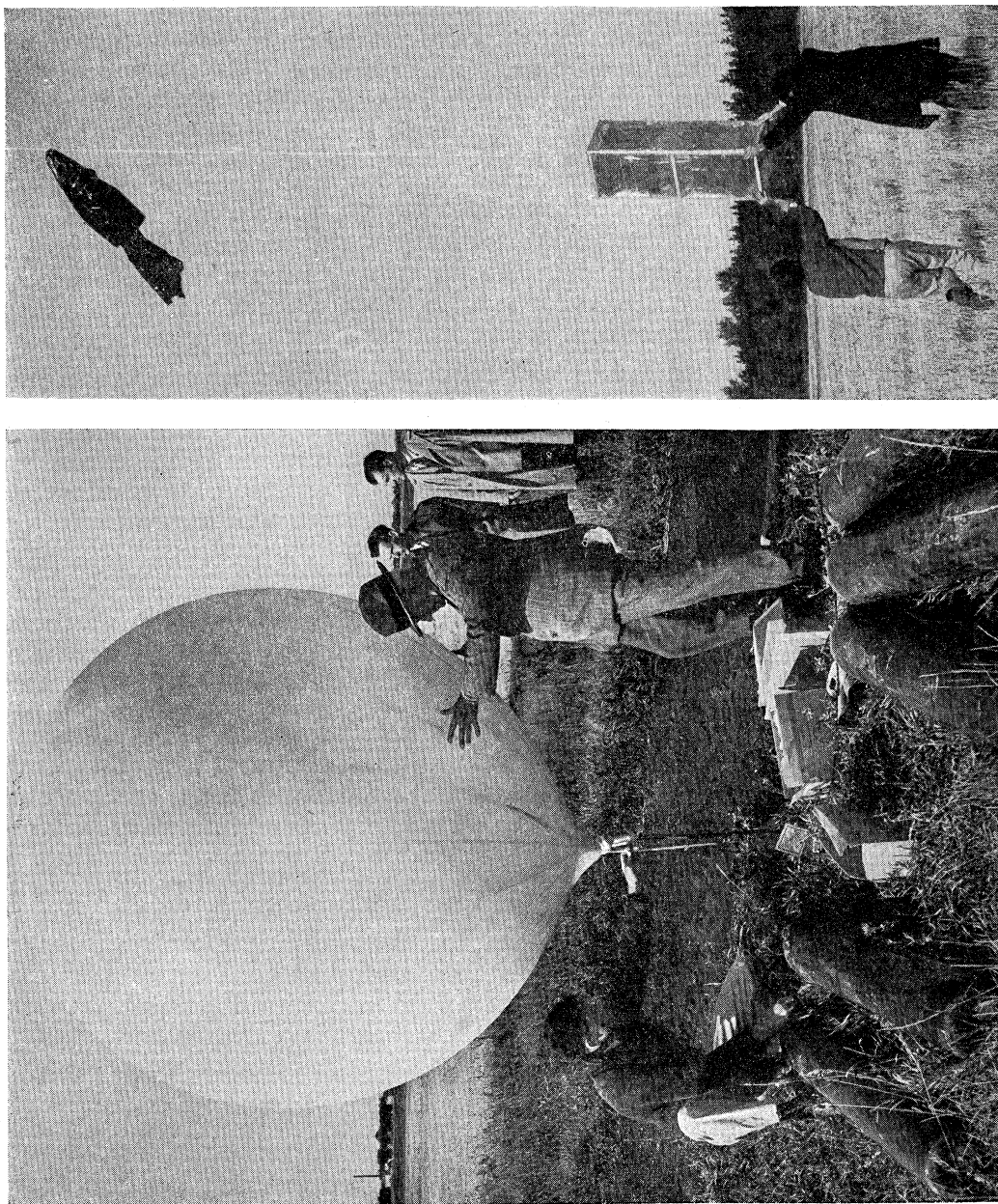


FIG. 1. (a) Final stages of the inflation of one of the balloons. H. V. Neher and R. A. Millikan in foreground. (b) Releasing the instrument. The flag near the top of the picture is used to attract attention to the instrument after it returns to earth. The metal frame and cellophane wrapping completely enclose the counters, amplifiers, etc.

percent at the maximum of the curve for a four minute interval. Errors resulting from correcting for efficiency and accidentals should be less than 0.5 percent. Errors in reference to the standard should be about 1.0 percent.

In reducing the counting rates to an absolute value, it is assumed that side showers are relatively unimportant. If it is desired to find the number of ionizing particles coming in from the vertical per unit solid angle per cm^2 per minute, the effect of upward radiation and showers from the top must also be taken into account. However, since in this paper we are concerned mostly with relative values of flights at different stations, we will assume that over the range in energies here dealt with these effects are roughly proportional to the total radiation and, hence, will not affect appreciably the comparison of the different flights.

The pressure data on the whole are quite satisfactory in these experiments. However, much of the uncertainty in these flights can probably be traced to errors in the barometer. It seems quite likely that the reason for curve 7, Fig. 2, at

Saskatoon crossing curve 5 at Rapid City at a pressure of about 0.1 atmosphere was a faulty barometer. Also curve 1 of Fig. 2 at San Antonio appears to be shifted to the right at the lower pressures when compared with the other curves. This may be due again to a faulty barometer.

An idea of the precision attained in these experiments can be obtained from Figs. 3 and 4. Here the experimental points for Bismarck and Rapid City are shown before they were corrected for accidentals and efficiency. It will be noted that the points for any one flight sharply define a curve for that particular flight. Furthermore, the two flights at either of these stations agree very closely. The curves after correction for efficiency and accidentals are also given in Figs. 3 and 4. The efficiency correction is about 7 percent at the maximum, the accidental correction less than 1 percent.

IV. DISCUSSION OF RESULTS

The most prominent features of the curves in Fig. 2 are: (1) the St. George curve is below that of Fort Worth, although St. George is 3° mag-

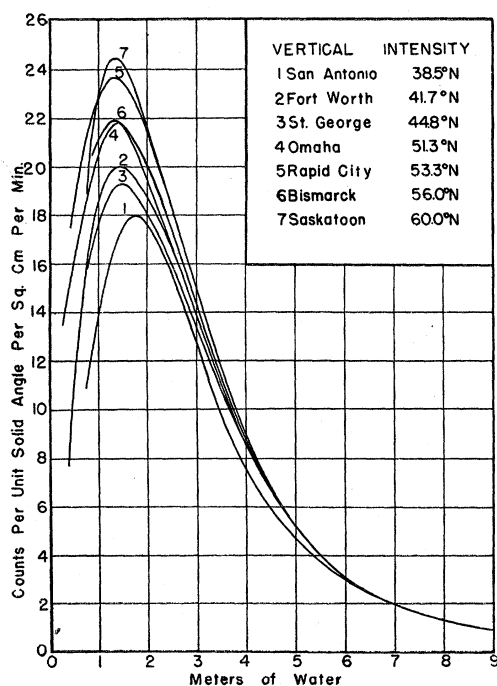


FIG. 2. Observed vertical intensity of the cosmic radiation as a function of pressure in meters of water, for indicated geomagnetic latitudes.

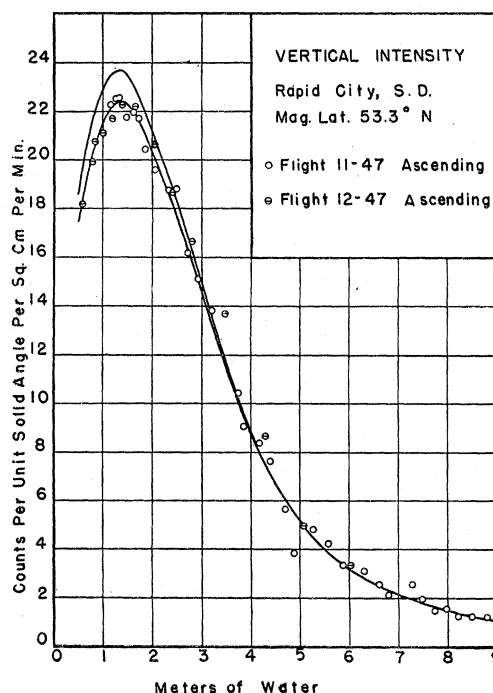


FIG. 3. Experimental data for Rapid City, S. D. The upper curve shows the result of correcting for accidentals and efficiency.

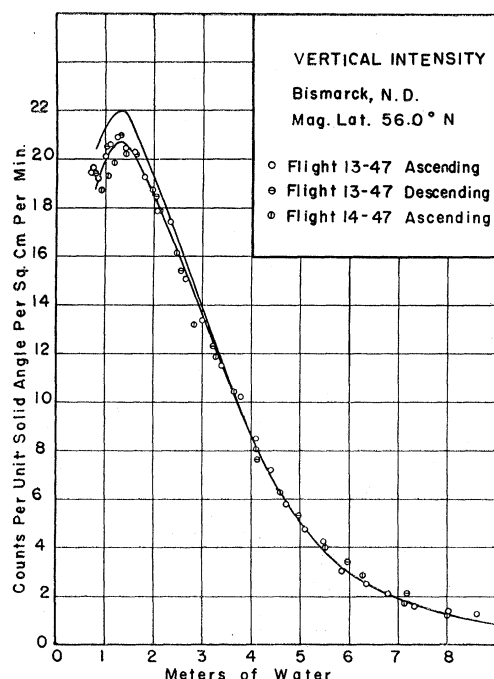


FIG. 4. Experimental data for Bismarck, N. D. The upper curve shows the result of correcting for accidentals and efficiency.

netic latitude farther north, and (2) the Bismarck curve (56°N) is below that for Rapid City (53°N). Such a result appears to be in definite contradiction to the results of the analysis of the motion of charged particles in the magnetic field of a dipole. This analysis predicts that cosmic-ray intensity should be a non-decreasing function of magnetic latitude. Figure 5 shows the effect more clearly. There we have plotted the maximum counting rates against latitude. The indicated probable errors are estimated from the uncertainties of the counting rates, the calibration against the standard, and the uncertainty in the efficiency and accidental corrections.

We have chosen the maxima of the curves as a measure of the amount of radiation coming in instead of the areas under the curves since small uncertainties in barometric pressure will affect the differences in the areas quite markedly but will have no influence on the peaks.

The probable error given for St. George is larger than the others. This is caused by the fact that both of the standards were accidentally damaged before the calibrations were made at

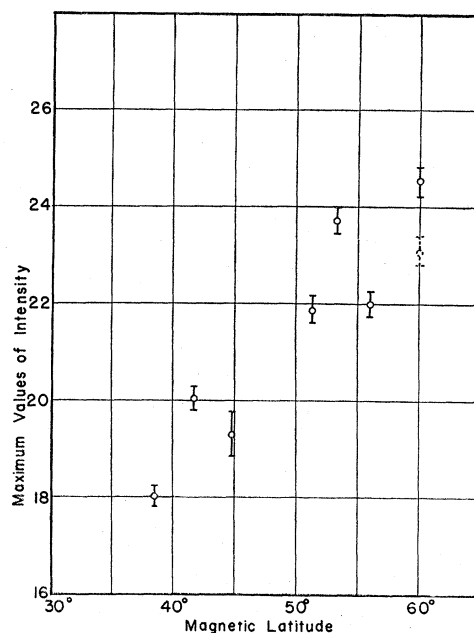


FIG. 5. Maximum vertical intensity as a function of latitude. The two flights at Saskatoon, lat. 60°N are shown separately. The lower point corresponded to a flight of questionable reliability.

this station. One was damaged only slightly and was taken as the standard at this location. Checks indicate that if there were changes they were less than about 2 percent. This large probable error makes it possible to say that perhaps the counting rate simply did not increase between Ft. Worth and St. George, rather than that there was a decrease. However, we also note that the flights at St. George were made three weeks after those at Ft. Worth.

The decrease from Rapid City to Bismarck cannot, we believe, be explained as experimental error. In discussing the data we have pointed out the limits of accuracy. This decrease is well outside these limits. The constant checks on all apparatus make it very doubtful that it was out of order at any time either at Rapid City or Bismarck. At no time during any of the flights did we have occasion to think that any of the counters had failed. Reference to Table I of the preceding article will show that several sets were used for more than one flight and when returned the calibration was always within a percent or two of that obtained before the flight.

The evidence from Fig. 5, then, is that during

this period of August 27 to September 23, 1947, there were fluctuations in the incoming cosmic-ray intensity that completely masked any small increases that one might wish to find in moving north from one station to another.

The agreement between the two flights at any one station was very good when made only a few hours apart. However, when made a day or more apart the agreement was not in general as good. This is shown in Table II where the times of the flights are given, together with the counting rates at the peaks of the curves.

The second flight at Saskatoon did not give a complete record. The release was made in a 25-mi. hr.⁻¹ wind and the antenna was accidentally bent. The signals were poor except for the first 20 minutes and also for a short time when the counting rate was at its maximum. In the opinion of the observers on duty at this time these signals were good. These data were sufficient to fix the peak of the curve. From Table II it will be noticed that the value at the maximum for the second flight is 5.6 percent lower than the flight made two days earlier. Because of lack of data at other elevations this flight is not included in the Saskatoon curve of Fig. 1 and is shown dotted in Fig. 5.

Such fluctuations over longer periods of time are known from electroscope data taken with balloons in former years. In 1938 flights at Bismarck showed more radiation coming in than at Saskatoon the year before.⁴ Also, the maximum value at Bismarck was 30 percent higher in 1940 than in 1938.⁵ Smaller variations have been found at Omaha and even as far south as Oklahoma City. The maximum of the ionization curve was 14 percent higher at the time of measurement at the latter station in 1940 than in 1938.⁵ However, at the two times flights have been made at San Antonio with electroscopes, 1936 and 1940, the same maximum values were found. These observations have been interpreted as time fluctuations of primary particles incident on our atmosphere in the lower energy range—the higher energy particles remaining essentially constant. (See reference 5).

⁴ Robert A. Millikan and H. V. Neher, *Proc. Am. Phil. Soc.* **83**, 409 (1940).

⁵ Robert A. Millikan, H. V. Neher, and William H. Pickering, *Carnegie Inst. of Wash. Year Book*, No. **43**, 56 (1943-44).

TABLE II. Flight data.

Flight	Station	Date	Release time	Maximum rate	Instrument No.
4-47	San Antonio	Aug. 27, 1947	1242	18.0±0.2	8
5-47	San Antonio	Aug. 28, 1947	1300	18.0±0.2	1
6-47	Fort Worth	Aug. 30, 1947	1537	19.9±0.2	3
7-47	Fort Worth	Aug. 31, 1947	1428	20.3±0.2	4
9-47	Omaha	Sept. 6, 1947	1205	21.6±0.3	4
10-47	Omaha	Sept. 8, 1947	1221	22.1±0.3	3
11-47	Rapid City	Sept. 10, 1947	1307	23.8±0.3	17
12-47	Rapid City	Sept. 10, 1947	1722	23.6±0.3	19
13-47	Bismarck	Sept. 12, 1947	1347	22.2±0.3	12
14-47	Bismarck	Sept. 12, 1947	1701	21.6±0.3	16
15-47	Saskatoon	Sept. 15, 1947	1301	24.5±0.3	4
18-47	Saskatoon	Sept. 17, 1947	1431	23.1±0.3	4
19-47	St. George	Sept. 23, 1947	1616	19.4±0.5	15
20-47	St. George	Sept. 23, 1947	2318	19.2±0.5	3

The time of release is Greenwich time. The maximum rate is given in coincidences per unit solid angle per cm² per minute.

Fluctuations over shorter periods of time have also been previously noted. Two electroscope flights made three days apart at Bismarck in 1938 gave results differing by 7 percent.⁴ Two flights one week apart at Bismarck in 1946 (data not published) differed by 13 percent. Similar flights made at Omaha 4 days apart in 1937 showed a difference of 5 percent.⁶

In seeking a reason for these fluctuations we first investigated the behavior of the earth's magnetic field and the sun during this period. Through the kindness of Dr. S. B. Nicholson of the Mt. Wilson Observatory we were given access to the data taken at Mt. Wilson. While the records showed considerable activity of both the sun and earth during this time there were no magnetic storms on the earth and no flares on the sun of major importance. Sunspots were prominent, since the sun was near the peak of its 11-year sunspot cycle, but none were particularly large during this period. We conclude from this study that if activity of the sun or changes in the earth's field were responsible for the variations at the high altitudes observed they were much greater than the usual fluctuations found at sea level.

To study further the nature of these fluctuations we examined ground level records of cosmic-ray intensity as measured with an ionization chamber at Cheltenham, Maryland (50.1° N. mag.). (These data were made available through the courtesy of Dr. S. E. Forbush of the Carnegie Institution of Washington.) At the time of the

⁶ I. S. Bowen, R. A. Millikan, and H. V. Neher, *Phys. Rev.* **53**, 855 (1938).

flights at St. George these records show a sea-level ionization significantly lower than during the other flights. Indeed a preliminary analysis shows that if one assumes a factor of 10 in the amplitude of the fluctuations at high altitude for all the flights as compared with the shielded ionization chamber at Cheltenham the apparent inconsistencies of Fig. 5 nearly all disappear.

In March 1942 no change in cosmic rays coming in near the vertical was measured between St. George and Pocatello.³ The flights reported here show a 12 percent increase between St. George and Omaha, Omaha being at about the same magnetic latitude as Pocatello. Likewise a 14 percent increase was found between Pasadena and St. George in 1942. In August and September 1947 no increase was found between Ft. Worth and St. George, Ft. Worth being at nearly the same magnetic latitude as Pasadena. We are now engaged in a program of analyzing data from balloon flights of past years to determine if these and other inconsistencies may disappear when ground level measurements are taken into account.

Other observers have reported no change at very high altitudes in the radiation coming in near the vertical north of certain magnetic latitudes. Johnson⁷ in 1938 reported no increase within his observational uncertainties between Minnesota (56°N) and Churchill, Canada (69°N). Likewise, Dymond⁸ in 1939 made several balloon flights at 85°N magnetic and found no increase over that reported by Pfozter⁹ at 49°N. We should like to point out that comparisons of flights taken at different times may not be valid and the apparent agreement between such flights may be fortuitous.

⁷ T. H. Johnson, *Phys. Rev.* **54**, 151 (1938).

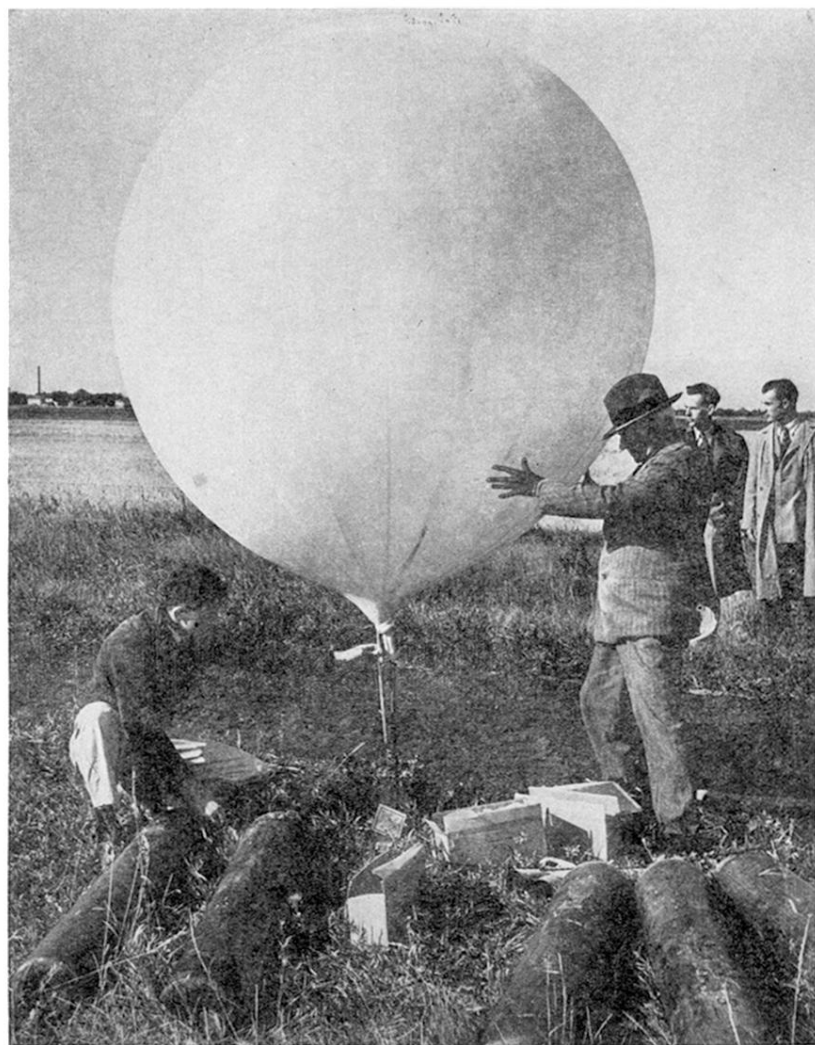
⁸ E. G. Dymond, *Proc. Roy. Soc.* **171A**, 321 (1939).

⁹ G. Pfozter, *Zeits. f. Physik* **102**, 23 (1936).

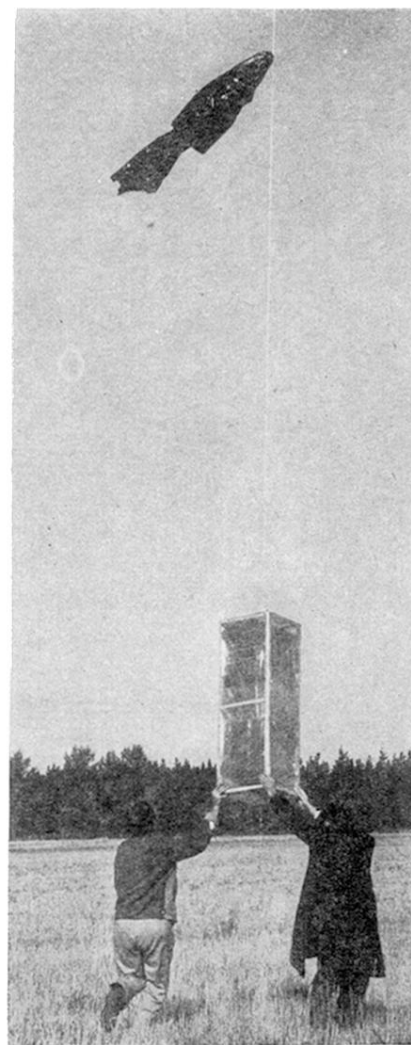
V. CONCLUSIONS

The results of 14 flights taken at seven more or less evenly spaced stations extending from San Antonio, Texas, to Saskatoon, Canada, indicate that fluctuations in the primary particles were quite pronounced during the period August 27 to September 23, 1947. These fluctuations were such as to hide any small increase one might hope to find in going north from one station to another. No plateau at northern latitudes was found. However, it may have been masked by the observed erratic behavior of the incoming radiation. No apparent correlation was found between the observed fluctuations and the activity of the sun or magnetic storms on the earth. There does, however, appear to be a correlation between fluctuations of cosmic rays at high altitudes and those found at sea level. The study of these variations in cosmic rays would require a large number of flights made over an extended period of time. The increment from one latitude to another could be obtained by sending instruments aloft simultaneously from two stations.

We wish to express our appreciation to Dr. R. A. Millikan, who accompanied us on this expedition, for his assistance and encouragement during the course of these experiments. The authors also wish to express their appreciation for the welcome given us by the University of Saskatchewan and the help of Professor E. L. Harrington, who was largely responsible for the success of our work in Canada. We gratefully acknowledge the financial assistance of the Carnegie Institution of Washington that made these experiments possible. Our thanks are also due the U. S. Weather Bureau for supplying us with helium for our balloons, and the individual members of the Bureau, who were of so much assistance at each of the stations in the United States.



(a)



(b)

FIG. 1. (a) Final stages of the inflation of one of the balloons. H. V. Neher and R. A. Millikan in foreground. (b) Releasing the instrument. The flag near the top of the picture is used to attract attention to the instrument after it returns to earth. The metal frame and cellophane wrapping completely enclose the counters, amplifiers, etc.